Impedance Matching Concepts in RFID Transponder Design

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Abstract

In this paper, we analyze impedance matching concepts in passive radio frequency identification (RFID) transponders, which are powered by the incoming RF energy and consist of an antenna and an integrated circuit chip, both with complex impedances.

The impedance match between the chip and the antenna can be characterized by the power transmission coefficient. We analyze the behavior of the power transmission coefficient and the effect it has on the tag performance.

As an example, we consider a specific RFID transponder design, an Intellitag ID card with embedded folded meander antenna operating in 915 MHz band. We present both measurement data and simulation results, which are in good agreement.

1 Introduction

RFID is a rapidly developing automatic identification technology [5, 1]. Although the basic principles of passive RFID technology were developed soon after Wold War II, it took nearly half a century before RFID technology advanced to today's level.

A typical back-scattered RFID transponder (tag) consists of an antenna and an integrated circuit (chip). The chip is usually placed right at the terminals of the tag antenna, and both chip and antenna have complex input impedances.

The system operates in the following way. Base station module (RFID reader) transmits an RF signal, which is received by an RFID tag antenna. The voltage developed on antenna terminals powers up the chip, which sends the information back by varying its input impedance and thus modulating the backscattered signal.

Proper impedance match between the antenna and the chip is of paramount importance in RFID [6]. It greatly determines important RFID tag characteristics, such as tag read range [2]. Impedance match can be characterized by the power transmission coefficient whose behavior determines tag performance and can be analyzed as shown below. A specific RFID tag design example with modeling and simulation results which agree with measurement data is also presented as an illustration of the analysis.

2 Impedance Matching

Consider an equivalent lumped circuit of RFID tag shown in Figure 1, where $Z_c = R_c + j\,X_c$ is the complex chip impedance and $Z_a = R_a + j\,X_a$ is the complex antenna impedance. The voltage source represents an open circuit RF voltage developed on the terminals of the receiving antenna. The chip impedance includes the effects of chip package parasitics. Both Z_a and Z_c are frequency-dependent. In addition, chip impedance Z_c may vary with the power absorbed by the chip. The antenna is usually matched to the chip at the minimum threshold power level necessary for chip to respond.

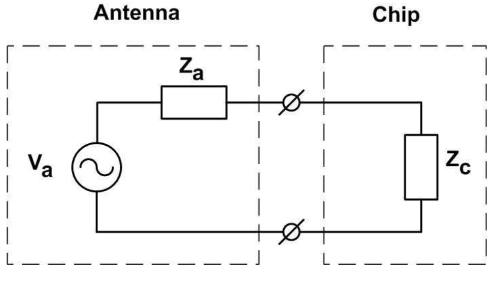

Figure 1. RFID transponder equivalent circuit.

The amount of power P_c that can be absorbed by the chip from the antenna is given by

$$P_c = P_a\,\tau\,, \tag{1}$$

where P_a is the maximum available power from the antenna and τ is the power transmission coefficient.

P_a is the power that can be dissipated at the chip when $Z_c = Z_a^*$. The power transmission coefficient τ is given by

$$\tau = \frac{4R_cR_a}{|Z_c + Z_a|^2} \tag{2}$$

and can be plotted directly in complex impedance plane as shown below. The power transmission coefficient τ directly characterizes the degree of impedance match between the chip and the antenna.

Normalizing Equation 2 by R_c^2 allows one to obtain

$$\tau = \frac{4r_a}{|1 + r_a + jQ(1 + x_a)|^2}\,, \tag{3}$$

where $r_a = R_a/R_c$ is normalized antenna resistance, $x_a = X_a/X_c$ is normalized antenna reactance, and $Q = X_c/R_c$ is the resonant factor of the chip for the given frequency and absorbed power. Antenna impedance can be normalized to the chip impedance because an RFID tag antenna is usually matched to a given RFID chip.

After several straightforward mathematical transformations, Equation 3 can be expressed as

$$\left[r_a - (2/\tau - 1)\right]^2 + Q^2\left[x_a + 1\right]^2 = \frac{4}{\tau^2}(1 - \tau)\,. \tag{4}$$

One can see that Equation 4 describes an ellipse with the aspect ratio Q and center located at a point $\{(2/\tau - 1), -1\}$. Figure 2 shows the contours of constant τ given by Equation 4 for two different values of Q.

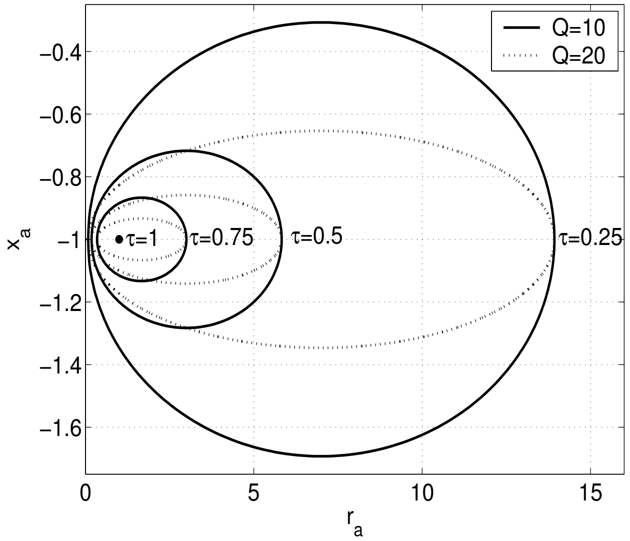

Figure 2. Contours of constant power transmission coefficient τ on normalized antenna impedance plane.

Since Z_a and Z_c are both frequency-dependent, both aspect ratio and foci of ellipses are also frequency-dependent. At a given frequency and power into the chip, any antenna impedance Z_a corresponds to a unique point $\{r_a, x_a\}$ and hence to a particular value of τ, determined by the ellipse passing through that point.

The contours shown in Figure 2 are a good illustration for impedance matching in RFID transponder. The smaller is the ellipse, the higher is the value of the power transmission coefficient. The point of perfect complex conjugate impedance match between the antenna and the chip is the point where $\tau = 1$.

3 Transponder Range

One of the most important characteristics of RFID tag is its read range. One limitation on the range is the maximum distance at which tag receives just enough power to turn on and scatter back. Another limitation is the maximum distance at which reader can detect this scattered signal. The read range is the smaller of the two distances. Typically, reader sensitivity is high enough so read range is determined by the former distance.

In free-space propagation environment, the power received by an RFID antenna can be calculated using Friis free-space equation as:

$$P_a = P_tG_tG_r\left(\frac{\lambda}{4\pi d}\right)^2\,, \tag{5}$$

where P_t is the power transmitted by the reader, G_t is the gain of the reader antenna, G_r is the gain of the receiving tag antenna, λ is the wavelength, and d is the distance between the reader and the tag.

If the minimum threshold power necessary to power up the chip is P_{th}, then read range r can be calculated as

$$r = \frac{\lambda}{4\pi}\sqrt{\frac{P_t}{P_{th}}G_tG_r\tau}\,. \tag{6}$$

The peak of the range in the frequency domain can be referred to as tag resonance. Typically P_t, P_{th}, G_t, and G_r are slow-varying, and τ is dominant in frequency dependence and primarily determines the tag resonance.

The read range in Equation 6 can be normalized to the maximum possible range of the tag when it is perfectly matched to the chip ($\tau = 1$). Such normalization allows designer to see what improvement in read range can be obtained by better impedance matching. For example for the tag in Figure 4, impedance matching with $\tau = 0.5$ corresponds to about 70% of the maximum attainable read range.

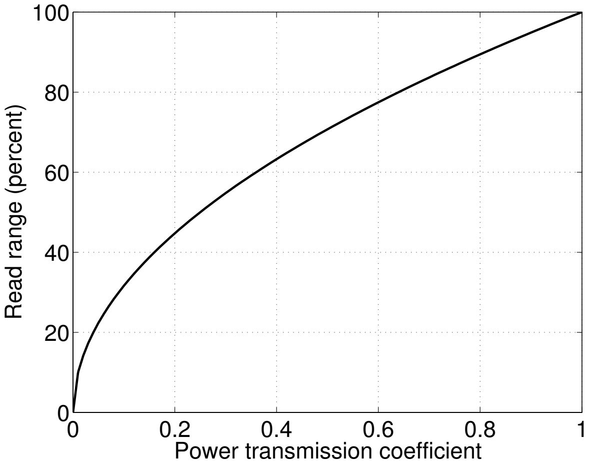

Figure 3. Normalized read range vs. power transmission coefficient.

4 Design Example

Consider a specific design example: the Intellitag ID card developed by Intermec Technologies Corporation [4] and shown in Figure 4. This credit card format RFID tag was designed for security access and control applications. This tag is currently used for expedited border crossings between the United States and Canada.

Figure 4. Intellitag ID card.

The transponder consists of an RFID chip connected to a folded meander copper antenna printed on 4 mil FR4 substrate (the copper trace area is 70 mm by 22 mm) as shown in Figure 5. This transponder was designed to operate in 915 MHz band after being embedded into a plastic card (blank or with magnetic striping).

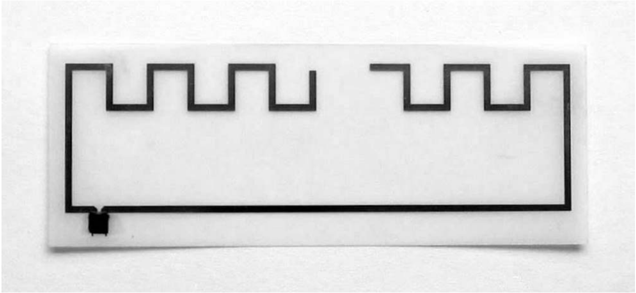

Figure 5. RFID transponder inside Intellitag ID card.

In this tag, Fairchild RFID ASIC chip [3] was used. The chip was mounted on antenna terminals using flip-chip packaging. The input impedance of the packaged chip was measured in the frequency domain with the network analyzer for different power levels. It was determined with RFID reader that the minimum power needed by the chip to turn on was -9 dBm and that the packaged chip impedance was $Z_c = 15 - j\,420$ Ohm.

This antenna was designed using electromagnetic (EM) simulation tool *Ansoft Designer*, which allowed us to calculate antenna gain and impedance and match it to the chip. The antenna was designed so that the tag resonates in free-space at about 965 MHz. This ensures that when the tag is placed inside plastic card, its resonant frequency shifts to 915 MHz band.

The power transmission coefficient for this antenna in free-space is given in Figure 6 as a function of frequency. It was calculated from Equation 2 where chip impedance value was measured as described above and antenna impedance was obtained from EM simulations.

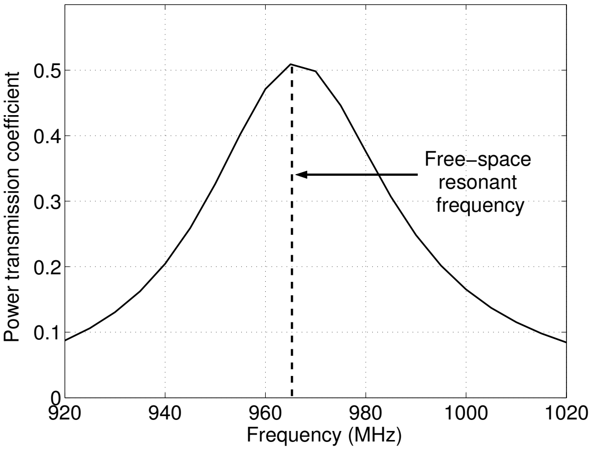

Figure 6. Power transmission coefficient of RFID transponder in Figure 5 in free space.

5 Experimental Results

The tag read range was measured as illustrated in Figure 7. The tag was placed in an anechoic chamber at a fixed distance from the linearly polarized reader antenna. The tag face was normal to the antenna centerline and oriented in the direction of best polarization match. The distance to the tag (0.9 m) was selected such that the tag would respond and be located both in far field. At each frequency, the minimum transmitter power P_t required to communicate with the tag was recorded by using controlled attenuation on the output of RFID reader.

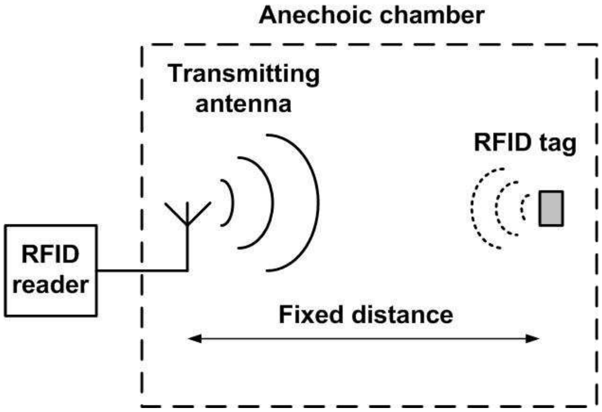

Figure 7. Tag range measurement setup.

Since the gain of the transmitting antenna, the separation distance, and the cable loss were known ($d = 0.9$ m, $G_t = 6.2$ dBi, $L = -0.5$ dB), the tag read range for a given EIRP was calculated from Equation 6 as:

$$r = d\sqrt{\frac{\mathrm{EIRP}}{P_t G_t L}}\,. \tag{7}$$

Figure 8 presents a comparison between theoretical and experimentally measured read range for our RFID transponder. Antenna gain G_r and impedance Z_a were calculated using *Ansoft Designer*, and chip impedance Z_c was measured as described above.

It can be seen that theoretical curves and experimental data are in good agreement. It can also be seen that the read range in free-space reaches maximum at the same frequency as the free-space power transmission coefficient shown in Figure 6.

When RFID transponder is placed inside plastic card, antenna properties change and tag resonant frequency shifts from 965 MHz to 915 MHz.

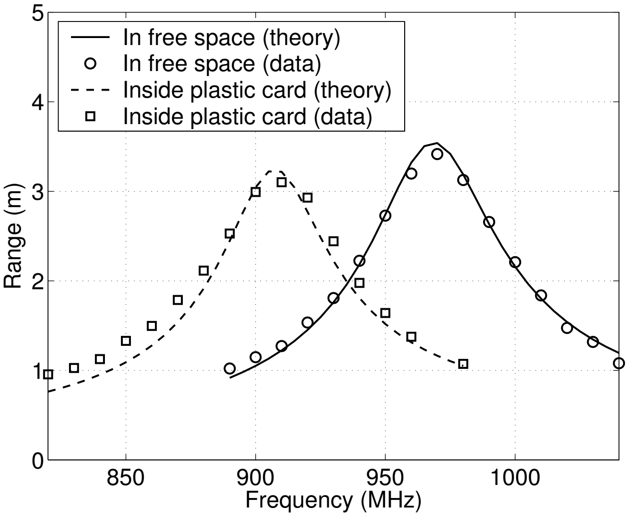

Figure 8. Theoretical and experimental read range of RFID transponder shown in Figure 5 (EIRP=4 W).

6 Conclusions

In this paper, we analyzed impedance matching concepts in RFID tags, in which both antenna and chip have complex impedances. The impedance match can be characterized by the power transmission coefficient. We analyzed a behavior of the power transmission coefficient and the effect it has on tag performance.

We presented a specific RFID tag example and showed that the tag resonance is determined by the peak in the power transmission coefficient. The experimentally measured read range agreed well with the theoretical model.

7 Acknowledgements

The authors would like to thank their colleague Mr. Thomas Miller for his interest in this work.

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